there is a need to stylize their language to everyday English and to use U.S. patent terminology. Accordingly, the cancellation of claims 1-16 and the addition of new claims 17-35 are not being presented for reasons of patentability as defined in Festo Corporation v. Shoketsu Kinzoku Kogyo Kabushiki Co., Ltd., 234 F.3d 558, 56 USPQ2d 1865 (Fed. Cir. 2000).

Respectfully submitted,

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Marked up Version of Specification

The present invention relates to a method for determining at least one time constant of a reference model in a cascaded controlling arrangement [in accordance with the preamble of claim 1].

Description of the Related Art

Usually a cascaded controlling structure, [consisting of] including a position, rpm and current control device, is employed in numerically controlled machine tools. As a rule, the speed control device, which is connected downstream of the position control device, is embodied as a PI speed control device and [comprises] includes a proportional branch (P) and an integral branch (I). The phase response of the upstream connected position control device worsens as a result of the effect of the integral branch of the speed control device. It is therefore necessary as a consequence of this to reduce the loop gain kV of the position control device a priori in order to prevent oscillations in the drive systems of the machine tool controlled by the controlling device. However, as large as possible a loop gain kV of the position control device is desired in principle.

SUMMARY AND OBJECTS OF THE INVENTION

It is therefore [the] an object of the present invention to disclose a method for determining at least one time constant of a 2nd order reference model, which is arranged in a cascaded controlling device of a machine between a position control device and an speed control device, and which assures an optimized control behavior

of the controlling device.

This object is attained by a method [having the features of the characterizing portion of claim 1] for determining at least one time constant of a reference model, which is designed as a 2nd order time-delay element of a machine. The method includes detecting an oscillation frequency of an undamped machine oscillation and determining an optimized value of a time constant of the reference model as a function of the detected oscillation frequency of the undamped machine oscillation.

The parameterization of a suitable 2nd order reference model for the most varied types of machines is now possible by [means of] the method of the present invention. Here, the resulting reference model essentially always assures that at least the undesired influence of the integral portion of the speed control device on the control behavior is eliminated.

Depending on the machine type, one time constant or two time constants are determined in accordance with the present invention, which determine the behavior of the reference model and therefore affect the control behavior of the controlling arrangement during the actual controlling operation. However, in accordance with the present invention at least the so-called second time constant of the reference model is basically determined as a function of a detected oscillation frequency of a continuous machine oscillation.

Surprisingly, or contrary to theoretical reflections, it is now possible by [means of] the steps of the present invention for determining the time constant to also compensate controlled systems with idle times and delay elements for machines which theoretically would require higher order reference models; this applies in particular to the above mentioned category of non-rigid machines with dominant natural frequency. The determination of theoretically exact nth-order reference models ($n > 2$) in such machines would be connected with a very large outlay. In contrast to this it is possible by [means of] the use of second order time-delay elements as the reference model, whose time constants are determined in accordance with the present invention, to keep the resulting outlay for parameterization of the reference model low.

The method in accordance with the present invention can be performed manually, as well as in an automated manner.

Further advantages, as well as details of the method in accordance with the present invention ensue from the subsequent description of exemplary embodiments by [means of] the attached drawings.

Shown here are in:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1[,] shows a block diagram representation of a part of an embodiment of

a cascaded controlling structure of a numerically controlled machine tool in accordance with the present invention;[,]

FIGS. 2a and 2b[,] show a flow diagram in each for explaining an embodiment of a method of the determination, in accordance with the present invention, of the time constant of a 2nd order reference model to be used with the cascaded controlling structure of FIG. 1;[,]

FIGS. 3 to 21, respectively, show different representations to be used with the cascaded controlling structure of FIG. 1, which will be explained in greater detail in the ANNEX.

The portion of the controlling structure represented [comprises] includes a position control device 10, as well as a downstream- connected speed control device 20. The actual controlled system 30 is arranged downstream of the speed control device 20 and is only schematically indicated. In the present example, the speed control device is embodied as a PI control device (proportional-integral control device); the integral branch 21, as well as the proportional branch 22 of the speed control device 20 are represented separately of each other in FIG. 1. A reference model 40 is arranged between the position control device 10 and the speed control device and is embodied as a 2nd order time-delay element, i.e. a so-called PT2 element. The reference model 40 simulates the behavior of the closed speed control device 20 without an integral portion and in this way assures that at least the

undesired influence of the integral portion, or integral branch 21, on the control behavior of the speed control device is eliminated. As already indicated above, by [means of] the steps to be explained in what follows it is possible in a surprising manner to also parameterize reference models which compensate controlled systems with idle times and delay elements. In theory it would be necessary to parameterize reference models with orders n > 2 for such controlled systems, which would be relatively expensive.

Contrary to theoretical considerations it [has now been] is shown by the present invention that the use of 2nd order reference models, whose time constants T1 and T2 are determined in accordance with the present invention, is even possible when the respective system would actually have to be simulated by [means of] a reference model of higher order n, i.e. n > 2. However, the mathematically exact representation of such a complex system by [means of] an appropriate nth order reference model would basically cause an extremely high computational effort. In actuality this has the result that by [means of] the use of a 2nd order reference model, whose time constants T1 and T2 are determined by means of the invention, it is possible to also optimize the control behavior of the speed control device 20 for machines which are part of the second category already discussed above. Here, by employing a 2nd order reference model, which [was] is parameterized in accordance with the present invention, in these systems, not only is the influence of the integral branch of the speed control device eliminated, but moreover the influence of additional delays, or idle times, in the controlled system is also minimized. It is

surprisingly possible to use loop gains kV in such systems with 2nd order reference models parameterized in accordance with the present invention, which are greater than possible loop gains kV in case of a non-existing, or switched off integral branch in the speed control device.

The operation in accordance with the present invention for determining the time constants T1, T2 for the 2nd order reference model will now be explained by [means of] the flow diagrams in FIGS. 2a and 2b.

The theoretical considerations on which the present invention is based will be explained in greater detail in what follows in the following ANNEX and several simulations and test results will be presented.

The method of the present invention and the arrangement of the present invention were tested by [means of] a mathematical simulation. This simulation which, besides the mathematical machine model, also contains the mathematical model of the present invention, will be described in what follows.

The mass inertia moment of the controlled system, together with the momentary constants of the motor, are the defining characteristics of the system. The following parameters are used in connection with this:

Mass inertia [J_l] J_L= 50 kgcm^2

Motor constant $k_{MC} = (1.5/\ 2) * (Nm/A_{eff})$, wherein A_{eff} is known in the art to

represent an effective motor current which is measured in Amperes

Therefore, the controlled system $G(s)$ is determined by:

$$G(s) = (num/den) = 1/(J_L * s).$$

The conversion from the radian frequency ω to U/s (U represents the number of rotations) takes place by [means of] a downstream-connected P-element with $1/(2 * \pi)$. A disturbance can be introduced via the input "momentary disturbance Ms", which simultaneously affects the momentary value and the actual rpm. This is intended to correspond to a typical disturbance because of a milling cutter action and is used to rate the disturbance rigidity.

For simulating realistic rpm-connected losses, a derivative feedback k'p of the internal system output to the momentary summing point takes place. By [means of] this a new controlled system $G'(s)$ is created:

$$G'(s) = (1/(J_L * s))/(1 + k'_p /(J_L * s)))$$

$$G'(s) = (1/(k'_p + (J_L * s))$$

$$G'(s) = 1/k'_p * 1/(1 + (J_L/k'_p * s))$$

A TP1 control device is created by [means of] this derivative feedback.

A model of the 1st order controlled system with disturbance introduction is represented in FIG. 3. As shown in FIG. 3, a signal lq is fed to an amplifier 300 that multiplies the signal lq by a momentary constant to generate a signal 302 that is fed to adder 304. A momentary disturbance signal Ms is fed to the adder 304. As shown in

FIG. 3, the adder 304 is connected to a control system 306 that generates the signal G(s) = (num/den) which is fed to a component 308 that generates a loss signal 310 that is a function of rpm. The loss signal 310 is fed back to the adder 304. The signal G(s) and the signal Ms are each fed to a second adder 312 that adds the two signals to generate signal 314. The signal 314 is then fed to an amplifier 316 to generate signal Msl.

Position control device amplification MP1510 [[m/min/mm]] m/min/mm = 15 P-factor (speed control device)

MP2500 [[As]] [As] = 9 I-factor (speed control device) MP2510 [[A]] [A] = 2200, wherein A represents Amperes.

The following physical values appear in this closes control loop:

P-factor speed control device: in [[As/U]] [As/U]
Motor constant: kMC/sqrt(2) in [[Nm/A]] [Nm/A]
Moment of mass inertia of the system [Jl] J_L

Thus, the conversion function G(s) of the open control loop is:

$$G(s) = MP2500 * k_{MC} * 1/(2 * \pi) * 1/([J_l]\ J_L * s)$$

$$k'_p = MP2500 * k_{MC} * 1/(2 * \pi)$$

$$G(s) = k'_p * 1/(\ [J_I\ ]\ J_L * s)$$

The conversion function H(s) of the closed control loop is:

$$H(s) = G(s)/(1 + G(s))$$

$H(s) = (k'_p /([J_I] \underline{J_L}* s))/(1 + (k'_p/([J_I] \underline{J_L}] * s)))$

$H(s) = 1/(1 + ([J_I] \underline{J_L}* s)/[K] \underline{k_p}')$

$H(s) = 1/(1 + T_1 *s)$

A PT1 element with the time constant T1 is obtained as the IPC reference model:

$T_1 = [J_I] \underline{J_L}/k_p' = ([J_I] \underline{J_L}*2 * \pi) /(MP2500 * k_{MC})$ (F1)

Heidenhain controls have an acceleration feedforward control, which can be set by [means of] a machine parameter. This machine parameter MP26 provides the reciprocal value of the angular acceleration α per current in [[As2/U]] <u>[As^2/U]</u>. The time constant of the IPC can be calculated in a simple manner by [means of] the angular acceleration.

Mel = Electrical moment [[Nm]] <u>[Nm]</u>
kMC = Momentary motor constant [[Nm/A]] <u>[Nm/A]</u>
[Jl] J_L = Moment of mass inertia [[kg.m2]] <u>[kgm^2]</u>
MP26 = Acceleration feedforward control [[As2/U]] <u>[As^2/U]</u>

$M_{el} = I_{MOT} * k_{MC}$

$\alpha = M_{el}/[J_I] \underline{J_L}$

$\alpha = (I_{MOT} * 2 * \pi)/MP26$

This is equal to:

$[J_I] \underline{J_L} /k_{MC} = (MP26)/2 * \pi$

This inserted in (F1):

$T_1 = [J_I] \underline{J_L}/k_p' = ([J_I] \underline{J_L}*2 * \pi) /(MP25 * k_{MC})$

T_1 = MP26/MP25 (F2).

In what follows, the various feedforward controls are sequentially switched in. To compare the effects, all simulation parameters were kept constant.

System Parameters:

Momentary constant [Ktc[Nm/A]] Ktc[Nm/A] = 1.5 * sqrt(2)

Momentary load inertia [Jl [kg.m2]] J_L[kgm^2] = 9

Rpm losses [[Nm/ω]] Nm/ω = 0.15

Control device circuit parameters:

Position control device amplification MP1510 [[m/min/mm]] m/min/mm = 9

P-factor (speed control device) MP2500 [[As]] As = 9

I-factor (speed control device) MP2510 [[A]] [A] = 2200

Interpolation parameters:

Jerk r [[m/s3]] [m/s^3] = 2 * [103] 10^3

Acceleration a [[m/s2]] [m/s^2] = 5

Speed v [[m/s]] [m/s] = 0.4 / 60

Position s [[m]] [m] = 4 * [10-4] 10^{-4}.

The resulting following error without feedforward controls is represented in FIG. 14. A maximum following error of approximately 45 [um] µm results, which is impermissibly high.

The resulting following error without feedforward controls is represented in

FIG. 15. A maximum following error during the acceleration phase of 10 [um] µm results.

The IPC with acceleration and jerk control is represented in FIG. 19. As shown in FIG. 19, a resultant signal 800 is formed as the combination of the signals r_soll, Tr, a_soll, T_1 and n_soll so that resultant signal 800 is fed to the IPC 802 which generates a signal 804 that is added with the signal n_ist so as to form a signal 806. The signal 806 is then fed to an integral branch 808 which in turn generates an output signal 810. The proportional branch 812 receives a signal 814 so as to generate an output signal 816 that is added with the output signal 810.

The structure of the speed control device block with feedforward control in the control device output is represented in FIG. 21. In particular, the structure includes six input signals 900, 902, 904, 906, 908, 910. The input signal 900 is fed to a switch 912. The input signal 906 is fed to an amplifier 914 where the amplified signal 916 is fed to an IPC model feedforward control 918 that applies the factor 1/MP2500. The resultant signal 920 is fed to switch 912. The switch 912 also receives a constant signal 922.

The signal 908 is fed to the IPC phase reference model control 924 that also applies the factor 1/MP2500 so as to generate signal 926 that is fed to switch 928. The switch 928 also receives signal 908 and signal 930. The switch 928 chooses one of the three signals 908, 926 and 930 and feeds them to an adder 932 that also receives signal 910. The added signal 934 is sent to a component 936 that applies the

factor P2510/2*s so as to generate signal 938.

As shown in FIG. 21, the signal from the switch 912 and the signals 902 and 922 are sent to a switch 940 that sends one of the three signals to both adder 942 and adder 944. The adder 942 receives the signal from switch 940 and signal 938 and adds the two to generate signal 944 which is sent to multiplexer 946. The multiplexer 946 also receives signals 956 and 965 and sends a signal 966 to an output.

Signals 902, 922 and 948, which is the result of the amplification of signal 904 by amplifier 950 are sent to switch 952 where one of the three is sent to adder 944. The adder 944 receives two other signals 954 and 956. Signal 954 is the result of amplifying signal 910 by amplifier 958. Similarly, signal 956 is the result of amplifying signal 960 via amplifier 962. Signal 956 is the result of adding signals 908 and 910 by adder 964. As shown in FIG. 21, the signals from the switches 940, 952 and signals 938, 954 and 956 are combined by adder 944 to generate signal 965 that is sent to an output.

[Claims] I Claim: